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Programmable, miniature video-loggers for deployment on wild birds and other wildlife

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Summary

1. Animal-borne miniature video cameras hold the potential to revolutionise field ornithological research, with their ability to collect detailed behavioural data from a bird's eye view, in places and contexts where conventional observation techniques would fail.

2. Here, we describe the development of a new generation of solid-state video-loggers that are cheap, lightweight, programmable and easy to use and that overcome many problems associated with earlier transmission-based technologies.

3. Our loggers weigh *c.* 12·3–13·6 g fully packaged for deployment and record up to 94 min of video footage, at 640 × 480 pixels and 19·7 frames per second, on a 4-GB micro-SD card. Loggers are fitted with a custom-designed, microprocessor-controlled timer that enables flexible duty-cycling, switching the unit on and off following a preprogrammed schedule. Packaged loggers contain a miniature very high frequency (VHF) radio-tag (battery life *c.* 5–9 weeks) for positional tracking of the bird before, during and after scheduled video shoots, and to enable logger recovery for data download.

4. To make our loggers suitable for deployment on wild birds, we developed novel techniques: (i) for the lightweight packaging of electronics (thin sheets produced from thermoplastic) and (ii) for the attachment of units to, and their controlled release from, subjects (UV-sensitive, rapidly degrading rubber tubing). Loggers can be manufactured at comparatively low cost (components are *c.* 94 GBP, plus *c.* 145 GBP for the VHF radio-tag) and are easily refurbished after recovery, making the technology suitable for large-scale deployments and projects on modest research budgets.

5. A study in 2009/2010, with logger deployments on 19 wild New Caledonian crows *Corvus moneduloides*, demonstrated that our new technology is field-worthy and that it can generate rich data sets on the foraging behaviour, habitat use and social interactions of an elusive bird species.

6. The young field of wildlife video-tracking is maturing quickly, and in only a few years, technology has advanced sufficiently to enable cost-effective, hypothesis-driven field studies of terrestrial birds, mammals and reptiles. Large-scale deployment of video-loggers can generate data sets of unprecedented information content, promising major quantitative insights in basic and applied ecology.

Key-words: animal-borne video and environmental data collection system, biologging, biotelemetry, habitat use, home range, very high frequency wildlife radio-tracking

Introduction

Many bird species are difficult to study through direct observation, because they are shy or live in inaccessible habitats. Following pioneering work in the 1960s, very high frequency (VHF) radio-telemetry has revolutionised the investigation of wild, free-ranging birds, by enabling quantitative analyses of home ranges, activity budgets and habitat use patterns (Kenward 2001; Millspaugh & Marzluff 2001). In recent years, satellite-based technologies have considerably improved tracking accuracy and data yield (Rutz & Hays 2009; Tomkiewicz *et al.* 2010), whilst offering the added advantage of reliable automated data collection. Despite these advances, however, the behavioural and social context of animal movements remains usually unknown in positional tracking applications (Rutz & Bluff 2008). In some species and study areas, it may be feasible for fieldworkers to home-in on tagged subjects to make direct observations, and both VHF and satellite tags can sometimes be fitted with additional sensors that collect complementary behavioural data (Kenward 2001; Cagnacci *et al.* 2010; Tomkiewicz *et al.* 2010). But the key strength of VHF and satellite telemetry is undoubtedly the estimation of an animal's location in space and time, and not the assessment of its behaviour in those locations.

Nowadays, field ornithologists have a rich tool kit of 'biologging' techniques at their disposal, for gathering data

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on the behaviour and physiology of wild, free-ranging subjects (reviews: Cooke *et al.* 2004; Naito 2004; Ropert-Coudert & Wilson 2005; Wikelski & Cooke 2006; Hooker *et al.* 2007; Davis 2008; Ropert-Coudert *et al.* 2009; Rutz & Hays 2009; Takahashi & Yoda 2010). Whilst many of these approaches have proved extremely productive, they generally require elaborate calibration and cross-validation, which is difficult to achieve for most study systems. More importantly, they often only measure one specific (proxy) parameter, and mapping of behavioural states frequently turns out to be incomplete or unreliable. In an ideal world, researchers would record a bird's eye view of their subjects' undisturbed, natural behaviour – including foraging, habitat use and social interactions – and subsequently combine this information with quantitative positional data. This would help them understand context- and habitat-specific variation in behaviour, with explicit spatiotemporal referencing. Bird-borne video cameras with integrated VHF radio-tags are the method of choice for such projects ('video-tracking'; Rutz *et al.* 2007; Bluff & Rutz 2008; Rutz & Bluff 2008). Cameras generate particularly rich data sets and, importantly, do not require complex device calibration and data decoding – video provides a direct, and usually unambiguous, record of the behaviours of interest.

Marine biologists pioneered the use of animal-borne video technology (Marshall 1998, 2008; Davis *et al.* 1999; review: Moll *et al.* 2007), but their tags – which can be designed to be neutrally buoyant when submerged – are far too heavy (in the order of 100s of grams to several kilograms) for deployment on most terrestrial animals. Recent advances in microelectronics and communication technologies have enabled the construction of miniature, animal-borne video cameras that are sufficiently small for avian applications (review: Rutz & Bluff 2008). The earliest devices (*c.* 72–73 g in air) were used on diving birds, such as penguins and cormorants, recording still images on internal memory (Takahashi *et al.* 2004; Watanuki *et al.* 2007, 2008; for more recent applications, see Sakamoto *et al.* 2009b; Grémillet *et al.* 2010). Just a few years later, a first study used actively transmitting tags (*c.* 14·5 g) to capture streaming video from a medium-sized, terrestrial bird species (Rutz *et al.* 2007), marking the technology's true transition from water to land (Rutz & Bluff 2008; for work with trained eagles, see Carruthers, Thomas & Taylor 2007). Whilst solid-state video-loggers (*c.* 27 g) have recently been deployed on hand-raised, habituated birds during unconstrained foraging flights (Yoda *et al.* 2011), these tags were not programmable, which substantially reduces their potential utility for studying wild subjects.

Here, we describe the development of a new generation of solid-state video-loggers that are cheap, light-weight, programmable and easy to use and that overcome many problems associated with earlier technologies. Whilst we focus on avian applications, and specifically our own work on crows, our cameras are suitable for a wide range of terrestrial and aquatic species, and we are confident that researchers will find it easy to adapt our basic design to suit their specific study requirements. For some general background on wildlife video-tracking, and further notes on tag design, mounting techniques and ethical considerations, we refer readers to the 'quick guide' by Bluff & Rutz (2008).

Equipment and protocols

BASIC DESIGN AND COMPONENTS

Our basic video-logger units consist of five main components (Figs 1 and 2; Table 1; Video S1): (i) mini DVR, (ii) battery, (iii) micro-SD card, (iv) microprocessor-controlled timer and (v) integrated VHF radio-tag. All components are commercially available, apart from the custom-built timer board, which we will describe in detail in the next section.

Over the last few years, several companies have independently developed cheap solid-state video cameras for entertainment and sports applications. These devices are easily found on the internet with an online search engine (search terms: 'mini DVR', 'spycam', etc.). As in the past, we do not wish to endorse particular products, as research applications will vary widely in their technological requirements, and

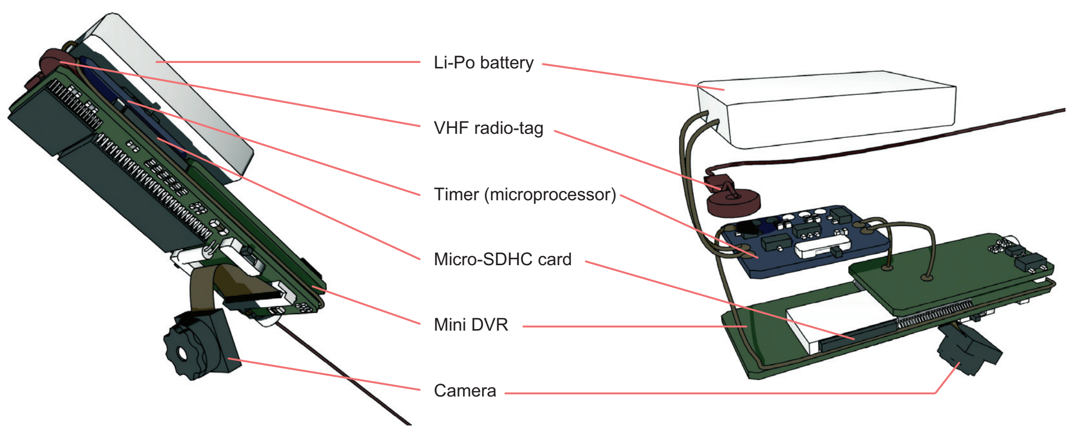

Fig. 1. Schematic illustration of a programmable, miniature video-logger for deployment on wild birds, showing an assembled, unpackaged unit (*left*) as well as the arrangement of all main logger components in an 'exploded' (and rotated) view (*right*). For an animation of this model, see Video S1, and for a photo of a logger packaged for deployment on a wild crow, see Fig. 2b.

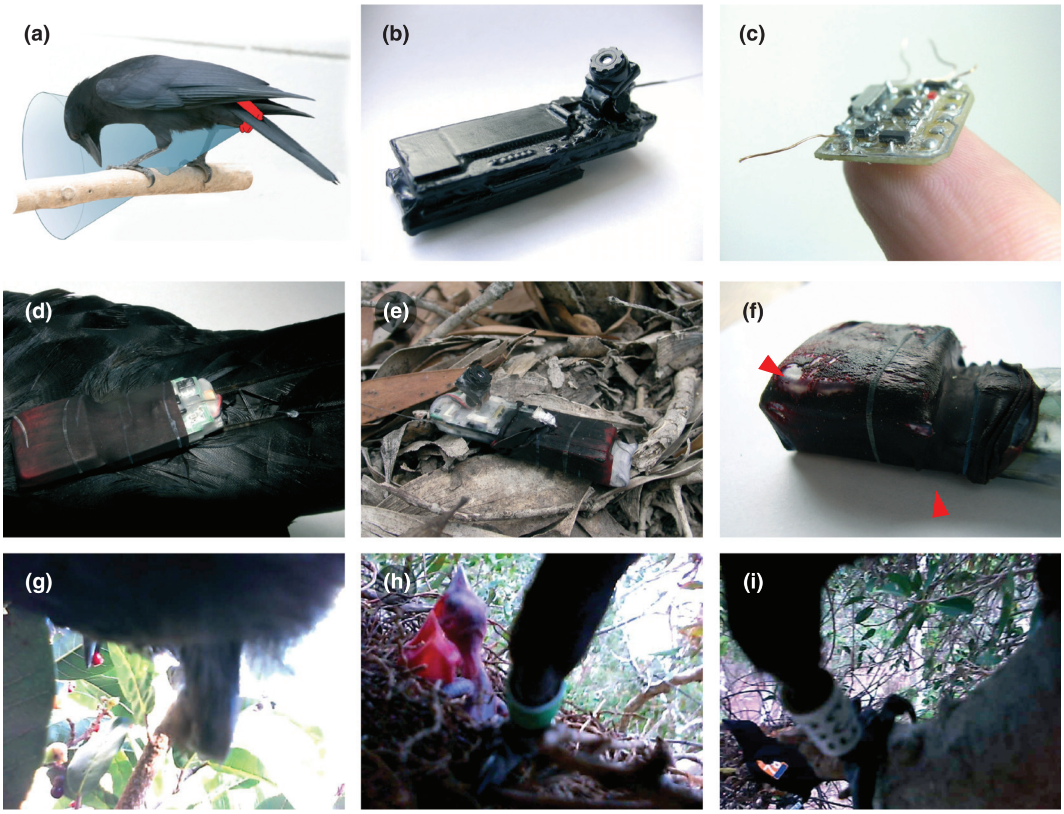

Fig. 2. Using video-loggers to study the undisturbed behaviour of wild, free-ranging New Caledonian crows. (a) Schematic illustration of the camera view (blue cone) afforded by a tail-mounted video-logger (red) (reproduced from Fig. 1 in Rutz *et al.* 2007). (b) A video-logger packaged in black polycaprolactone thermoplastic for deployment on a wild crow (*cf*. Fig. 1, *left*). (c) A custom-designed, microprocessor-controlled timer enables sophisticated duty-cycling of video-loggers (*cf*. Fig. 4); four short sections of enamelled copper wire are soldered to the timer board as they would be in a unit that interfaces a camera board (*cf*. Fig. 1, *right*). (d) Attachment of a logger, with a section of rubber balloon, at the base of the two central tail feathers of a crow (the bird's head is pointing to the left, out of view). (e) Shed logger found in the forest by tracking the signals emitted by an integrated very high frequency radio-tag (*cf*. Fig. 1). (f) Damage (red arrows) to the rubber balloon used for attachment, after logger recovery. (g–i) Sample still images taken from crow-borne video footage (g, handling red berry; h, at nest with two young chicks; i, filming another wing-tagged crow – see bottom-left corner).

product turnover in consumer electronics is so fast that it is impossible to make lasting recommendations (*cf*. Bluff & Rutz 2008). This said the exact board configurations do not matter, as long as the camera unit is small, produces video-recordings of sufficient quality (our units record at 640 × 480 pixels and 19·7 frames per second) and has a camera orientation that achieves the desired field of view (it is advantageous if the camera head is not attached to the board directly, but via a flexible cable).

Once the logger has been extracted from its plastic or metal casing, significant further weight savings can be attained by removing any nonessential components. Often substantial parts of the main logger board can be trimmed away, in addition to removing redundant (mini-)USB connectors, SD card holders (cards can be glued into place instead) and/or microphones (if audio is not required). In the interest of animal welfare, units should also be made as light as possible (Wilson & McMahon 2006), even for larger species. In case of our particular loggers, we can reduce the mass from 39·6 g for the factory-supplied unit (without micro-SD card) to 6·2 g for a stripped unit that is ready for further modification (without micro-SD card and battery). Depending on battery configurations and other specifications (see below), the deployment mass of a fully packaged logger varies between 12·3 and 13·6 g (mean ± SEM, 12·91 ± 0·08 g, $n = 19$ loggers), which is significantly less than our earlier actively transmitting video-tags, which ranged between 13·4 and 15·8 g (14·54 ± 0·21 g, $n = 18$ tags, Rutz *et al.* 2007; *t*-test, $t_{22} = -7{\cdot}26$, $P < 0{\cdot}001$; *cf*. Fig. 3a); for reference, a British two-pound coin weighs 12·0 g. Lighter units can of course be constructed using smaller batteries, but at a penalty to video-recording duration.

To power the video circuit, we use a single 3·7 V lithium ion polymer (Li-Po) battery (see Bluff & Rutz 2008). With our current logger design, a nominal 220 mAh battery of *c*. 4·6 g yields *c*. 70 min of video footage, whilst a 300 mAh battery of *c*. 4·9 g will generate *c*. 85 min (for a case study, see below). We replace the factory-fitted battery of our units with a 1-C Li-Po cell without over-discharge controller (Tenergy Corp., Fremont, California, USA), as this allows us to maximise video yield by completely discharging the battery during deployment (which may damage the cell and prevent re-use).

We use standard 4-GB micro-SDHC cards, with class-4 writing speeds to ensure seamless video capture (e.g. SanDisk). The advantage of using SD cards for data storage, rather than

Table 1. Approximate cost (in Pound Sterling, rounded to the nearest pound) and mass (in grams) of individual components required for building a programmable bird-borne video-logger; this list refers to our basic design for wild New Caledonian crows. In addition to logger components, a video-tracking project requires some basic tools for logger assembly (soldering iron and consumables, multimeter, Li-Po charger, butane heat gun, assorted small tools, including forceps and scalpels), programming (computer, PICkit^{TM}-2 with USB cable and microprocessor interface) and deployment (rubber balloon sections or tape, superglue), as well as for data analysis (micro-SD card reader, video analysis software)

Components	Cost (GBP)[1]	Mass (g)[2]
mini DVR[3]	70	6·20
Timer (microprocessor)	14	0·66
Li-Po battery[4]	3	4·55
4GB micro-SDHC card	6	0·26
Copper wiring	0	0·05
Packaging materials[5]	1	0·50
VHF radio-tag[6]	145	0·47
Total	239	12·69[7]

VHF, very high frequency.
[1]All quoted prices refer to 2010–2011 and exclude costs incurred through research and development, shipping of components and labour for logger assembly.
[2]There is some variation in the mass of components. In particular, packaging can be adjusted to provide the desired level of protection (more robust = thicker = heavier).
[3]Manufacturer-supplied casing removed, and logger board stripped off all excess material (without micro-SD card and Li-Po battery, but retaining the microphone).
[4]A single 220 mAh cell (width × length × height, *c.* 14 × 34 × 5 mm), without over-discharge protector.
[5]Thin layer of Polymorph, which makes the tag splash but not waterproof.
[6]Biotrack PicoPip-2 tag, with minimal tag potting, fitted with a 1·55 V Ag379 silveroxide cell (expected battery life 5 weeks) and a single alloy antenna.
[7]There is some variation in component mass, and extra weight savings can be achieved through relentless removal of excess material; the smallest logger built was 12·32 g (see main text).

nonextractable, board-mounted flash memory, is that they are hard-wearing and straightforward to remove from loggers that have been physically damaged or submerged in water. Micro-SD cards are currently available in up to 16 GB, and for most avian video-tracking applications, loggers are likely to be battery – rather than memory – limited. We review remote data download and endless memory options in the Discussion section below.

As with our earlier transmission-based video-tags (Rutz *et al.* 2007; Bluff & Rutz 2008), our new video-loggers are fitted with a small VHF radio-tag that enables positional tracking of the tagged animal as well as recovery of the shed logger for data download (for further details, see below). PicoPip tags from Biotrack Ltd. (Dorset, UK) are amongst the smallest commercially available radio-tags, and we have found them to be particularly suited for our application. We usually stock a range of tags fitted with Ag379 (0·25 g) and Ag376 (0·40 g) 1·55-V silveroxide batteries, which give *c.* 5 and 9 weeks of radio transmission, respectively. To save weight, we ask the manufacturer to supply tags with only a thin coating of Plast Dip® (Plasti Dip International, Blaine, Minnesota, USA), but without dental acrylic potting. When packaging units, the VHF radio-tag is positioned at the proximal end of the logger, and its antenna is guided alongside the logger body, projecting distally away from the unit (Fig. 1). We have our VHF tags fitted with light-weight, nonkink alloy antennae. An additional ground-plane antenna (which is shorter than the main antenna and mounted perpendicular to it) can increase VHF tracking range at a minimal weight cost, which could be essential for tag recovery in wide-ranging species or projects in challenging terrain. For systems where birds can be easily re-trapped for logger recovery, and where tracking of tagged birds is impossible or unproductive, such as seabirds that reliably return to their breeding burrows, video-loggers can be deployed without integrated VHF radio-tag, substantially reducing device costs (Table 1; Fig. 3c).

MICROPROCESSOR-CONTROLLED TIMER

Commercially available video cameras do not provide the programming facilities that are necessary for effective deployment on wild subjects, but they may be suitable, after minimal modification, for work with habituated or trained subjects (Carruthers *et al.* 2007; Yoda *et al.* 2011). To maximise the utility of video-loggers as a research tool, scientists need to be able to switch loggers on and off at preprogrammed times. Such 'duty-cycling' of units includes the following tasks (Fig. 4): (i) to switch the logger off for an initial habituation period (to allow the bird to recover from trapping/tagging), (ii) to schedule recording to coincide with the species' activity peaks (to increase the likelihood of documenting rare, or interesting, behaviours) and (iii) to record footage in evenly spaced, short recording bouts (to accumulate quantitative, standardised 'daily-diary' data).

We have developed a microprocessor-controlled 'timer unit' that is capable of achieving these functions (Fig. 2c; hardware was designed and built by Ron Joyce, in collaboration with C.R.). Our timer enables us to 'take control' of a wide range of commercial camera systems, by simulating the manual button presses that would normally be used to operate units. It works with cameras that have a 'standby' function and require two button presses to start recording, as well as with simpler configurations that involve the operation of only one button. Electronically, the timer uses a PIC10F206 RISC microprocessor (Microchip Technology Inc., Chandler, Arizona, USA); a P-channel FET switches the battery power to the camera, and an open collector NPN transistor simulates the button pushes that initiate and end video-recording. To minimise weight, surface-mount components are used on a 0·8-mm PCB. Assembled boards can be sealed with a thin layer of protective coating for applications where physical damage is likely.

Being an 8-bit processor, and for simplicity of software design, the maximum length of any timing interval is limited to 255 units. All key parameters of the duty-cycle can be programmed (within certain bounds) individually for each logger (for details, see Fig. 4). Sleep and recording bouts can be programmed, so that the video-logger either shuts down before

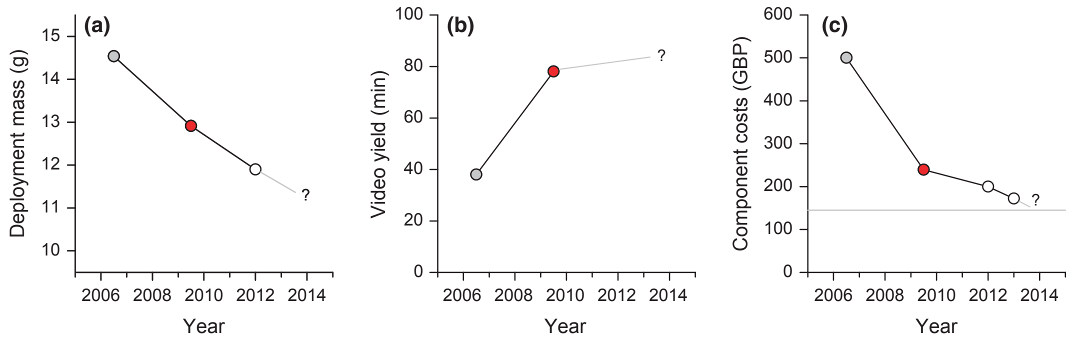

Fig. 3. The commercial development of small video systems for mass consumer markets drives: (a) the miniaturisation of loggers (deployment mass of loggers used for research on New Caledonian crows), (b) increased logger performance (video footage captured per tag that yielded footage) and (c) the decrease in component costs (for a crow tag). Data shown for 2006/2007 and 2009/2010 are for units deployed by Rutz *et al.* (2007) (grey symbols, $n = 18$ actively transmitting video-tags) and in this study (red, $n = 19$ solid-state video-loggers), respectively; white symbols are for prototypes, and grey lines and question marks indicate future trends. The horizontal grey line in panel (c) shows the approximate cost of a small very high frequency (VHF) radio-tag (145 GBP), which is by far the most expensive component of current and future video-loggers. With regard to prototypes, we have recently started working on two different units: prototype-1, shown in panel (a), attempts to minimise logger size and mass (the logger has a more compact build than the design described in the present study and is marginally lighter at *c.* 10·92 g, with a 220 mAh battery and micro-SD card but without VHF radio-tag and packaging); prototype-2, shown in panel (c) for the year 2013, attempts to minimise component cost (the video board costs only 3 GBP, including postage; the assembled logger is slightly larger than our current units, at *c.* 6·5 g without packaging, but offers better recording quality, at 1280 × 960 pixels and 30 frames per second).

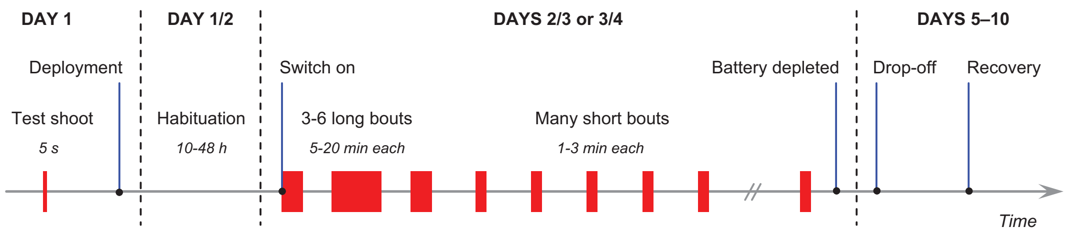

Fig. 4. Schematic illustration of the on–off duty-cycle for a routine video-logger deployment on a wild New Caledonian crow, as implemented by a microprocessor-controlled timer unit (*cf.* Fig. 2c). Before final packaging, and deployment on a bird, a brief test video (5 s) is shot, to confirm that the logger and timer are working flawlessly and that the camera lens is in focus (if the logger lacks time-stamping, a reference clock is filmed at this stage). For the first 10–48 h, the logger is set to remain on 'standby', that is, the camera is not filming; this preserves battery power whilst the bird recovers from trapping/tagging and habituates to the device. On the first morning of video-shooting, several long bouts of 5–20 min each are timed to coincide with the species' known early-morning activity peak, maximising chances of recording foraging behaviour and social interactions. Subsequently, the logger records *ad battery mortem* brief bouts of 1–3 min each per hour, enabling quantitative assessment of activity budgets when data are collected for multiple birds. The duration of all recording bouts, and of all interbout intervals, can be programmed individually, and different duty-cycles can be used for different (groups of) birds. The battery of the integrated very high frequency radio-tag lasts for several weeks, so the logger can be recovered once it has dropped off (*cf.* Fig. 2e). The time axis and the red blocks indicating bouts of video-recording are not drawn to scale and not all recordings of an actual deployment are shown.

the battery is permanently damaged, or alternatively, operates *ad battery mortem* (see above). The booting-up of loggers takes *c.* 10–20 s; if video-loggers lack time-stamping capabilities (as is the case with our current design), this start-up time needs to be taken into account both when scheduling video shoots and when back-calculating times for observed behaviours.

The microprocessor code is written in assembly language (software was written by Ron Joyce, in collaboration with C.R.), which reduces space requirements and allows for maximisation of sleep/recording periods. MPLAB® IDE v8.43 compiler (Microchip Technology Inc.) is used to assemble the code and program the microprocessor. Each logger can be programmed with a unique duty-cycle, affording maximum flexibility in terms of tailoring units to specific study objectives or logistical constraints. The timing periods are held in an 'include' file that is incorporated into the code when the compiler is run; this means that the timing information can be configured using a simple text editor (such as Notepad; Microsoft, Redmond, Washington, USA), reducing the risk of introducing erroneous source code changes. The timer's firmware and timing periods are programmed in the field using the microprocessor's in-circuit programming capability. We use a PICkit™-2 programmer (Microchip Technology Inc.) that connects to a computer with a standard mini-USB–USB cable and to the timer through a five-pin custom-built interface.

PACKAGING OF LOGGERS

As video-loggers are currently battery limited, their data yield is best maximised using the highest capacity (largest) battery permissible for a final target logger mass (see above), whilst minimising the weight of all other components. Substantial weight savings can be achieved with the packaging of units, and we have spent considerable resources on developing techniques that are superior to our earlier heatshrink-based approach (Bluff & Rutz 2008).

We make thin sheets of packaging material from polycaprolactone thermoplastic (Polymorph; Middlesex University Teaching Resources Ltd., Herts, UK), which are heated gently with a heat gun before being wrapped around and brushed onto the logger unit. This way the casing of a logger consists of a very thin plastic sheet that is extremely light (Table 1), yet has sufficient integrity to protect the unit from damage (Fig. 2b). Our Polymorph packaging makes loggers splash proof and facilitates component recycling through easy reheating and unwrapping. Our study species has a powerful bill, and although some units were damaged by birds during the first few hours post-tagging, we have found our technique to be adequate in the majority of deployments; our attachment technique with rubber balloons (see below) provides an additional layer of protection across the main body of the unit.

We produce thin sheets of Polymorph by heating a single layer of thermoplastic beads in the oven for *c.* 5 min at 120 °C, then rolling them into a uniform sheet of *c.* 1·5 mm thickness. This sheet is then drawn across a preheated *c.* 200 °C hot board of tempered glass to produce even thinner sheets (*c.* 0·1–0·2 mm thickness). The desired thickness can be achieved by altering the speed at which the sheet is drawn across the hot glass.

Our loggers can be packaged for deployment on diving seabirds, using a combination of heatshrink (for the main body of the logger; material as described in Bluff & Rutz 2008), machined perspex housing (for the camera head) and fish tank silicone sealant (for sealing the heatshrink–perspex interface). A unit that was successfully attached to a Manx shearwater *Puffinus puffinus* in 2011 had a deployment mass of 16·05 g, recording 34 2-min video bouts over a 2-day period (C. Rutz and T. Guilford, unpublished data).

MOUNTING TECHNIQUES

As with our earlier video-tags, we mount units on the base of the central tail feathers, with the camera head pushed through the feathers and bent forwards to provide an 'under-belly' camera view (Fig. 2a; Rutz *et al.* 2007). This technique positions the unit close to the bird's centre of gravity, provides unobstructed camera view during foraging (i.e. whenever the bird bends forward, its head appears in view of the camera) and, importantly, enables safe logger release after footage has been captured. Unlike transmitting units, our new video-loggers need to be recovered for data download (Fig. 2e,f), so they must be attached nonpermanently – sufficiently long to enable completion of the scheduled video shoots, but no longer than necessary.

With our loggers, which are optimised for deployment on crows, video shoots are typically completed 2–4 days after tagging, so we developed an attachment technique that would reliably release units after *c.* 5–10 days (Fig. 4). Generations of field biologists have tried, without much success, to develop reliable and safe release mechanisms for terrestrial wildlife biologging devices. Trialled techniques included weak-link harnesses, glues, surgical thread and even small amounts of explosives. Some of these techniques have been found to put animals at risk because they occasionally result in partial release (e.g. partly opened harnesses can entangle birds; Millspaugh & Marzluff 2001), whilst others have unreliable release timing or are too heavy for smaller species.

After extensive pilot testing, we settled on a very simple and cost-effective design: short sections cut from rubber air balloons. We use so-called rocket balloons (e.g. Henbrandt Ltd., Ipswich, UK), which when deflated have suitable external dimensions (long and narrow) and wall thickness (medium). We prefer cheap makes as they tend to degrade quicker than better-quality balloons, but studies that require longer-term logger attachment may need to opt for more durable materials.

The attachment principle is simple: we insert the activated, packaged logger into a tube of balloon (slightly longer than the logger) that is held open by metal tongs; we then 'feed' the bird's two central tail feathers through the balloon tube, to sit underneath the logger, but inside the balloon; once the logger is positioned at the base of the central tail feathers (and is not interfering with the preening gland), the metal tongs are carefully withdrawn – the balloon will contract and 'clamp' the logger in place, without the need for any glues (Fig. 2d). A small rectangular piece of polystyrene, glued centrally to the underside of the logger, sits tightly between the two central tail feathers and prevents them from crossing over. Where the camera lens is pushed through the central tail feathers, a few feather barbs may need trimming, so that they do not obstruct camera view; only a few millimetres will need to be cut from a very small number of barbs. The VHF antenna can be attached to the shaft of one of the tail feathers with a few drops of superglue (which prevents it from moving around uncontrollably, which in case of our alloy antennae is noisy), keeping in mind that attachment should be weak enough to break when the main logger unit falls off. Exposed superglue can be set instantaneously with an activator spray (e.g. Loctite 7455 Activator; Loctite, Herts, UK) or simply a drop of water.

Other mounting techniques and camera angles may be preferable for other study species, as we have discussed in detail elsewhere (Bluff & Rutz 2008). For example, in a recent deployment on a shearwater (see above), units were mounted on the back of the bird with a few strips of Tesa® tape (Hamburg, Germany; *cf.* Guilford *et al.* 2008).

FIELDWORK

As our new video-loggers store all video data onboard, fieldworkers do not have to be present during video shoots, substantially simplifying fieldwork logistics in comparison with our earlier transmission-based technology (Rutz *et al.* 2007; Bluff & Rutz 2008). We still advise, however, that scientists make good use of the loggers' integrated VHF radio-tags and monitor the movements of tagged subjects before, during and after video shoots (Rutz *et al.* 2007; Bluff & Rutz 2008), as it is the combination of video data and positional (radio-tracking) information that produces particularly rich data sets (Rutz & Bluff 2008). We disagree with the view that the use of bird-borne video cameras is incompatible with productive radio-tracking (Millspaugh *et al.* 2008). Video-tags/loggers contain powerful VHF radio-tags that enable the collection of many weeks, or even months, of positional data, which is plentiful for conducting conventional home range and habitat use analyses (Rutz & Bluff 2008). In other words, video-loggers offer research opportunities very similar to those of normal VHF radio-tags, but add substantial value by generating precious, complementary video material.

Once on the bird, the logger follows its preprogrammed duty-cycle (Fig. 4). The balloon attachment gradually degrades because of sun (UV) exposure and will develop small holes after a few days (Fig. 2f); these holes release the balloon's tension, allowing the logger to slide off the tail feathers (for more details, see Case Study). Detached loggers (Fig. 2e) are easily found using well-established cross-triangulation and search techniques for low-lying, stationary VHF radio-tags (Kenward 2001).

Case study

Between 12 December 2009 and 18 January 2010, we deployed 19 video-loggers on wild New Caledonian crows *Corvus moneduloides*, as part of our ongoing research on the species' tool use behaviour (review: Rutz & St Clair 2012; for results obtained with our first-generation video-tags, see Rutz *et al.* 2007). We weighed all subjects upon trapping and fitted small birds with video-loggers with a 220 mAh Li-Po battery and larger ones with units with a 300 mAh battery. As in the past, we ensured that all video-loggers weighed $\leq 5\%$ of the birds' body mass ($4{\cdot}3 \pm 0{\cdot}1\%$, range 3·7–5·0%).

Early unit recoveries highlighted attachment and design weaknesses (seven of 14 deployed loggers recovered), which we were able to address in subsequent deployments. In a small number of cases, VHF radio contact to loggers/birds was compromised, or completely lost, a few days post-tagging, and some recovered loggers showed substantial damage to the VHF antenna and/or VHF battery connection. We responded to these observations by moving the VHF radio-tag into a more protected position, partly sandwiched between the two logger boards (Fig. 1). Furthermore, antenna curling was prevented by loosely attaching the antenna to one of the tail feathers (see above). One bird had detached the camera head before filming started, resulting in total loss of video footage. In subsequent designs, we therefore reinforced the camera's ribbon connection to the logger board with carbon fibre or Polymorph material. Finally, tail feather barbs obstructed the camera view in one subject, resulting in 53% of video footage being of insufficient quality for analysis, which was much higher than for all other cases (see below). Therefore, care was taken in subsequent deployments to trim the few barbs on the two central tail feathers that could potentially obscure the camera lens (see above). Following these modifications, the logger recovery rate increased to 80% with no loss of footage or significant feather obstruction (four of five deployed loggers recovered, with the fifth unit still attached to a bird at the end of the field season).

Overall, we recovered 11 of the 19 deployed loggers, yielding a total of 766 min of footage from 10 loggers; one unit had detached after 31 min of recording, leaving a total of 713 min of footage from crow-borne cameras. A large proportion of this material was of sufficient quality for basic analysis of the crows' approximate location (697 min, 98%) and behavioural activity (549 min, 77%). In our sample of recovered units, those fitted with the larger battery yielded an average of 85 min of footage per deployment ($n = 4$), whilst those with a smaller battery averaged 71 min ($n = 6$); the range of filming duration was 60–94 min.

Full analyses of our video data will be published elsewhere. Nevertheless, our study clearly demonstrates that our new technology is field-worthy and can generate rich data sets on the foraging behaviour, habitat use and social interactions of an elusive bird species (for sample footage, see Video S2, and for sample still images, see Fig. 2g–i).

Discussion

Our novel wildlife video-loggers not only overcome problems associated with earlier, transmission-based designs, but they are considerably smaller than other solid-state loggers and have sophisticated programming facilities.

Cost-efficiency was one of our main development goals, and we managed to meet our ambitious target of producing a unit at < 250 GBP component costs. If current trends continue, a fully functional video-logger will soon cost only little more than a conventional VHF radio-tag (Fig. 3c). Given the low, and rapidly decreasing, cost of basic components, video-tracking has now become available for projects on tight budgets or those that aim to deploy very large numbers of units. We believe that the latter approach holds particular promise, as it will enable the accumulation of quantitative data sets for the testing of clearly defined *a priori* hypotheses (Moll *et al.* 2007; Bluff & Rutz 2008; Millspaugh *et al.* 2008; Rutz & Bluff 2008).

In the near future, video-loggers will no doubt become even smaller and lighter, whilst recording for longer time periods at higher resolution and frame rates (Fig. 3a,b). Zinc-air batteries, like those used in hearing aids, are attractive alternatives to Li-Pos, as they have a considerably higher energy density and could therefore substantially reduce overall logger mass. The cells' 'breathing' hole (for collecting oxygen from the air as a cathode reactant) makes them vulnerable to water leakage in humid habitats, but a thin sheet of Gore-Tex® (Newark, Delaware, USA) may afford sufficient protection. Alternatively, units could be fitted with solar panels – an approach that could be exceptionally useful in combination with remote download facilities and endless memory solutions (see below). Our tests suggest that it should be possible to integrate flexible solar panel sheets (such as cells from PowerFilm Inc., Ames, Iowa, USA) into birds' wing-tags where they could occupy a comparatively large surface area and enjoy good sun exposure.

In terms of improving further the functionality of video-loggers, we have identified two main development goals. The first one is to develop event-triggering technology that could be used to activate loggers selectively in certain environmental or behavioural contexts, thereby maximising the information yield per minute of video footage recorded. Basic designs could simply monitor one extrinsic variable (e.g. light intensity, temperature, humidity and noise levels) and switch-on loggers above/below a preset threshold value. A more substantial, and more promising, advance would be the integration of sensors that enable the monitoring of behavioural states of the tagged subject itself. In some study systems, it may be possible to achieve useful triggering with mercury switches that respond to body orientation (Kenward 2001; for an application, see Fig. S2 in Rutz *et al.* 2007) or movements of certain body parts (Hall sensors; Wilson *et al.* 2002), but in others, two- or three-axial accelerometers may be necessary to map more complex movement patterns (such as repetitive head or body movements during foraging; review: Nathan *et al.* 2012). Whilst achieving the required computing speed in miniature animal-borne devices will be a major engineering challenge, we envisage the implementation of on-board, real-time analysis of acceleration signals that could be used for triggering video shoots whenever diagnostic signatures are detected (by suitable algorithms, such as wavelet transformation, Sakamoto *et al.* 2009a). In this context, it is worth mentioning that animal-borne video-loggers could make major contributions to the rapidly expanding field of animal social network analysis, by (selectively) filming behaviour during social encounters; integrated digital transceivers could be used to trigger cameras whenever they have received sufficiently strong radio pulses from other tagged animals (i.e. when two animals are within a preprogrammed distance of each other; see Rutz *et al.* 2012).

The second major development goal is the implementation of technologies for remote data download. Whilst our simple drop-off system works well with our study species, benefitting from deployment in tropical habitats where high UV exposure accelerates the degradation of the rubber tubing used for attachment, other projects may depend on remote data download. In recent years, such facilities have been developed for GPS loggers, which cannot only use satellite uplinks, but transfer data packages to field-deployed or manually operated receiver stations (Tomkiewicz *et al.* 2010). A promising plug-and-play approach would be to fit video-loggers, like those described in this study, with wifi-enabled SD cards (Eye-Fi; www.eye.fi). These cards have the same dimensions as conventional SD cards, but offer the added capability of transferring data remotely to wireless networks. The transmission range of these cards is currently only 20–30 m, but it should be possible to use the integrated VHF tag of video-loggers to locate tagged birds at their night roost, to enable targeted data download over short distances. Another concern is that the wifi transmitter of these SD cards draws current from the host device, which in case of our loggers would further reduce recording times. This would be a problem for our crow loggers, which at a deployment mass of around 12 g are severely battery limited, but it would be acceptable for larger loggers (for bigger animals) or solar-powered units (see above). It has not escaped our notice that the geotagging capabilities of Eye-Fi cards could be elegantly exploited for positional tracking of tagged subjects. In urban environments, video-loggers fitted with these cards could use ubiquitous wifi networks to offload their video files whilst recording positional data, producing image material that is explicitly linked to an animal's movement trajectory (*cf*. Rutz *et al.* 2007; Bluff & Rutz 2008; Rutz & Bluff 2008).

With decreasing unit costs and enhanced recording capabilities, innovative techniques for analysing increasingly large video data sets will become necessary (Davis 2008; Rutz & Hays 2009). Kentaro Sakamoto (personal communication) recently developed two extremely promising procedures for automated screening of large volumes of still images: (i) image colour composition estimation (analysis of colour expression patterns through *k*-means clustering) and (ii) image complexity estimation (edge index). These approaches have already been integrated into the software suite 'Ethographer' (http://bre.soc.i.kyoto-u.ac.jp/bls/index.php?Ethographer; Sakamoto *et al.* 2009a), and we are confident that future extensions will make them suitable for analysing video footage. Because of its potential significance in numerous military and civil applications, machine vision is an active research field, which may generate software solutions in the near future that could aid the analysis of animal-borne video imagery (J. Guerci, in Marshall 2008).

Concluding remarks

The widespread commercial availability of basic plug-and-play miniature video cameras means that scientists planning video-tracking projects can focus on the design of a suitable microprocessor for logger control, and the optimisation of species-specific packaging and mounting techniques. In the present study, we have described a logger design and attachment procedure that should be suitable for many terrestrial bird species, in a wide range of habitats. For some species, units may require stronger packaging, or firmer attachment, than described here for our crow loggers. This should be easy to achieve, but would inevitably increase logger deployment mass. We have already demonstrated that our loggers can be fully waterproofed for attachment to diving seabirds (see above) and that back-mounting units can sometimes enhance the field of view. But, our technology is not limited to avian applications, as only minor modifications would be necessary for deployment on mammals (attachment to collars or ear-tags), reptiles (packaging for gluing to the skin), or even fish or cetaceans (using pressure-proof alloy housing; see Takahashi *et al.* 2004).

As predicted just a few years ago (Bluff & Rutz 2008; Rutz & Bluff 2008), avian video-tracking has evolved rapidly from a fairly expensive, cutting-edge technology, to a cheap (Fig. 3c) and comparatively straightforward research tool. We have described above some future development goals, as well as possible solutions to foreseeable challenges, which should further enhance the utility of this technology. Recent trends indicate that, like VHF- and satellite-based technologies previously (see Introduction), video-tracking will be driving a major technological revolution in wildlife research, providing unprecedented insights into the hidden lives of a wide range of bird species and other animals.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Video S1. Three-dimensional computer animation of an unpackaged video-logger, showing the positioning of all main components (*cf*. Fig. 1).

Video S2. Sample video footage collected with an animal-borne video-logger attached to a wild New Caledonian crow (adult delivering food to nestlings) (*cf*. Fig. 2).